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MAJOR ADVANCEMENTS IN FABRICATION OF LARGE TITANIUM AIRCRAFT STRUCTURE

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PRESENTED AT THE 1968 MATERIALS ENGINEERING EXPOSITION & CONGRESS

14-17 OCTOBER 1968

DETROIT, MICHIGAN

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TECHNICAL REPORT NO. D 8-26.1

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Major Advancement in Fabrication
of Large Titanium Aircraft Structures

C. C. Lacy

Start

Efforts at The Boeing Company are directed toward rate production of titanium for both supersonic and sub-sonic airplanes. The sizes of parts will range from very large parts to thousands of small parts. Production rates as high as one million parts per month are forseen in the 1975 time period. This paper discusses new concepts of hot forming and hot sizing die fabrication such as a precision casting method and brings up to date the production experiences utilizing this technique. New generation hot forming equipment on order are reviewed.

A brief progress report is presented on an Air Force sponsored titanium section hot roll forming contract in which return flange hat and zee sections are formed to precision tolerances.

The fabrication of the 747 titanium landing gear beam assemblies is presented and includes both forming, machining and assembly operations.

to p 1

The author is associated with The Boeing Company, Seattle, Washington.
This paper is scheduled for the 1968 Materials Engineering Congress and Exposition, Detroit.

This seminar has been created because of an industry-wide feeling that the long projected titanium era has finally arrived. This may be true, but we see only a growing child not yet of adult size. Using Boeing as an example, approximately 25,000 titanium parts per month are typical of current program requirements. Looking toward the future, the production SST program, added to anticipated sub-sonic growth in titanium usage will swell this rate over 1 million parts per month. Studies of the impact such rates will have on facilities should be viewed only when sitting down.

Boeing is typical of other members of the industry in the approach toward production rate fabrication of titanium parts and assemblies. The value of titanium structure, design-wise, is fairly well established and would justify more usage if the cost were not so high. These costs have been primarily in non-recurring costs, such as facilities and tool families rather than the actual fabrication recurring costs. Past experience has shown that the ratio of non-recurring costs has often approached a factor of 2 to 1 based on 200-ship production programs. This indicates that while detail part fabrication costs are certainly important, the most fruitful area for cost reduction will lie in the facilitization and the development of more economical tooling families. Much of the effort up until now has been devoted to increasing our capability to fabricate titanium, whereas progress made in reducing the cost has been minimal. Success depends upon both developing greater capability and on lowering costs. The following topics have been chosen to highlight Boeing efforts in both categories.

New Forming Techniques & Equipment

It is possible to form parts to almost any normal configuration by some combination of processes. The parameters for processing such as limits for cold and hot forming, the need for inter-stage annealing or stress relieving, oxidation protection, and acceptable thermal cycles are established. Parts capable of being formed at room temperature on conventional equipment are processed routinely. Parts requiring hot forming or hot sizing operations because of part complexity or material property shortcomings constitute the fabrication challenge. The direction of progress in the area of forming is toward hot draw-forming for intricate, complex parts; hot creep-forming for gentle surface type parts; and to hot progressive roll-forming for sections for circumferential frames and for body stringers.

Hot Draw-Forming. The hot draw-forming process combines in a single step the former processes of preforming and hot sizing. Hot draw-forming is done on a new generation of presses having in addition to heated upper and lower platens, hydraulically actuated cushion pins protruding through one or both platens. Figure 1 illustrates the action of such a press having cushion pins protruding through the lower platen only. The purpose of the cushion pins is to provide an independent force to keep the draw ring portion of the part flat and yet permit material to be drawn from this area into the severely formed area. The cushion pins also eject the finished part. Boeing has four such presses on order with more contemplated. Advantages of the process are greater forming capability, shorter processing time, and in some cases, lower total tool family costs.

Vacuum Creep-Forming. Parts with mild contours with or without variable material thicknesses from tapering or sculpturing can be formed by vacuum creep-forming on ceramic dies. The process is adaptable to both integrally or externally heated dies. On 6Al-4V, two to eight psi vacuum pressure will form parts heated to temperatures of 1300 to 1400°F.

Section Forming. Forming of long sections such as hat or zee sections are best done on hot progressive rolling equipment for large quantities and hot draw bench for lesser quantities. Heat application methods are being developed for both processes. Induction and resistance heating as well as quartz lamp heating have been proven feasible. This latter method will be discussed in more detail in connection with a Boeing-Air Force research contract.

New Tooling Concepts

Most of the hot forming or hot sizing operations are performed in matched metal tools. These are the most expensive type of tools in the entire titanium processing family. In planning for the SST Prototype program, it will be necessary to fabricate matched metal dies at a rate of 1300 a month during a six month time period. If these dies had to be profile milled on conventional equipment, there is insufficient equipment in the entire United States to handle this program.

Precision Cast Tools. As one solution, Boeing initiated a research contract with an independent research organization to develop a method of precision casting stainless steel dies for this purpose to avoid the costly profile milling operation. The initial results of this program have already been reported. Basically, an H-H, Type II alloy from the American Casting Institute was selected as the alloy material. A process for casting was developed which was a modification of the currently patented Avnet-Shaw process. It has been shown by a number of production parts that the process is capable of yielding dies of sufficient accuracy and requiring a small enough amount of handwork to justify our faith in the process. Experience has shown, however, that many innovations will be necessary before this process can be considered a production operation. One item is to provide reference planes in the initial pattern by which the completed casting can be checked to determine if any warpage has occurred during the casting process, prior to the time the final die spotting operation takes place. This will eliminate many costly hours of handwork in order to get the die to the proper configuration. Some difficulties have occurred from dies supposedly fabricated from the H-H alloy composition. Any significant variations will show up as either warpage, possibly cracked dies, or different dimensions as a result of different characteristics of the material from which the die was made. The most encouraging part of the precision cast tool program, however, is the fact that an additional source has been developed for the fabrication of these dies. The discouraging note, is the fact that for 1300 die sets per month, there are insufficient pattern makers in the industry to handle this load.

Ceramic Tools. Another way of making matched die sets is the use of ceramics, and Figure 2 illustrates such a tool. Construction of these dies begins with a mild steel sub-base. The bulk of the die is built up with fused silica foam blocks, and the surface is fused silica cement. Heating elements are traditionally either heavy wires from material such as Nichrome 5 or Inconel 1/4-inch OD tubes which can be used for both heating and for cooling. Experience with both systems has been excellent. With matched ceramic dies which are integrally heated, it is only necessary to have a relatively inexpensive four poster press for doing the hot forming or hot sizing operation.

It is possible to use ceramic dies, in which only a single die is used as the female cavity and the vacuum forming process is used with external heat supplied by quartz radiant lamps supported on mobile carts. This process is used for gently formed parts, and requires the ability to seal the titanium blank around the periphery of the tool in order to pull the internal vacuum. The advantage of this single die vacuum forming system is the lack of requirement for matched tools of any kind. Any innovation which can eliminate the requirement for matched tooling is certainly a step forward in the correct direction toward reducing the costs of the system.

Glass Dies. Another innovation being pursued at Boeing is the use of glass as a forming medium. In aluminum fabrication, a trapped rubber head in a hydropress has been used to form parts over a male die for many years. This process, however, is not suitable for use at elevated temperature, so some effort was made to determine if some other medium could be used instead of rubber and still permit the use of elevated temperature forming operations. Feasibility studies have established that glass can be used in such a manner. A metal punch is used in the upper portion and in the lower portion, a steel box filled partially with glass is used for the matching die. A boro-silicate glass is chosen. The die cavity filled with the glass is heated up to approximately 1600°F. At this temperature, its viscosity is low enough so that the punch can be lowered into the glass and will actually imprint a cavity which matches the punch. The die is then cooled to 1300 to 1400°F (normal forming temperatures) and flat blanks can be placed between the upper punch and this glass cavity and titanium parts can be formed repetitively. The quality of the detail parts are exactly as though they had been done in matched metal tools. Some limitation exists however in the ability of this tooling concept to iron out compression wrinkles. The advantages of this system are quite evident when it is realized that the bulk of the cost of fabricating tools is making the die set match within the tolerances of the material. If this system can be perfected, it is necessary only to have the male punch meet the drawing requirements or approximately ± 0.030 tolerance and the glass cavity will fit the punch exactly. Shortcomings which are evident at this time are the tendency of the glass to stick to both the part and the upper punch. It is believed that this problem can be resolved by the addition of proper parting agents such as used in the diffusion bonding process. An example is a water slurry of boron-nitride.

Air Force Contract F 33615-67-C-11-64 Titanium Roll Forming

The next topic will be a brief progress report on the work done on a research contract with the Air Force Materials Lab., Manufacturing Methods Branch--Contract F 33615-67-C-11-64. The subject of this contract is "Development of High Temperature Continuous Rolling Process for Forming Minimum Bend Radii Titanium Sections". The basic objective of this program is to develop a production process for the continuous forming of typical hat and zee sections used in quantity in modern aircraft

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structures. These sections are to be formed with minimum bend radii, with a target of 1t or the bend radii equivalent to the material thickness. The specific configuration will be return flange hats and return flange zees with the material gage thickness of 0.050. The final stage of the contract will be the production rolling of the 500-feet in each section and in each of two alloys, 6Al-4V titanium alloy and 8Al-1Mo-1V titanium alloy.

Rolling Facility. Figure 3 is a schematic of the facility which has been built up to perform this contract. There are two major sections of the facility; the first is a preheat chamber which has the job of heating up the coil stock from room temperature to 1400°F and feeding it into the roll stands. The other portion is a basic progressive rolling machine which, as shown in the picture, has its own heating system to heat up both the rolls and the production part as it passes between the rolls. Quartz radiant lamps have been used in both the preheat chamber and in the roll chamber. Both thermocouples and optical pyrometers are used to monitor the part temperature, roll temperatures, and other equipment temperatures. Feed rates through the rolling machine are as slow as 5 ft/min and as fast as 40 ft/min. Tests have shown that the preheat chamber is capable of heating the coil stock up to 1400°F at the rate of 40 ft/min. The shafts of the rolling machine are water cooled to protect the bearings from the heat inside the roll chamber. The base of the rolling machine is a plenum chamber through which the incoming cool air is brought into the machine. This air passes up through passages in the side walls of the chamber to cool the reflecting gold coating to keep it under 1000°F and also to cool the ends of the quartz lamps below 600°F. The exhaust gases are collected in a duct system and exhausted from the building. Thermocouples are imbedded in both the forming rolls and in the shafts themselves. The output from these thermocouples is transmitted through Slip-ring commutator type pickups at the end of each shaft and recorded on suitable temperature recorders. Structural test type load cells are installed on each stand of rolls to monitor the pressures being used on each side of the rolls. By balancing these load cells, it is possible to exercise precise control of the rolling operation, creating straight parts. This experience has been limited to the hat section however, which is a balanced section. The unbalanced zee section will require straightening and the rolling machine is equipped with a straightening device know as a "Turks Head" unit which will be placed as a final stand of the machine.

Rolling Tests. Tests have been completed on the return flange hat section using roll staging as depicted in Figure 4. Results of initial rolling tests have indicated that critical mold line dimensions can be held within 0.006 and that bend angles can be held within 2 minutes. Minimum bend radii from 6Al-4V sheet material has been 1.3t. Tests on continuously rolled strip material have shown that the transverse properties are poorer than in the longitudinal direction and that on 6Al-4V alloy 1.5t appears to be the smallest bend radius achievable. The bend radii for the 8Al-1Mo-1V titanium alloy will be even greater.

747 Landing Gear Beam

An example of large production hardware is the landing gear beam for the 747 airplane. This assembly, approximately 20-feet long weighs 1760 pounds net and started as 8600 pounds of raw titanium stock.

pg 5

Spar Chord Forming. Each beam is made up of four of the largest titanium extrusions made, and of one large plate. The processing involves preheating, flattening, hot forming, stress relieving, machining, and assembly. Figure 5 shows the as-received extrusion and the formed and machined chord. The extrusions are first protectively coated and then preheated by resistance heating as shown in Figure 6. Hot forming the bends is accomplished in a hot sizing press as shown in Figure 7. Following the forming operations, the extrusion is stress relieved and then machined. Four such details make up each beam for a total of eight per airplane.

Web Forming. The web of the beam is made from 1-inch plate, flame cut to rough peripheral trim. Prior to machining, the plate is flattened using a vacuum forming process on an integrally heated ceramic die. Figure 8 shows two webs in the fixture after flattening. The webs are then machined and returned to the die for bending. The far end of the die contains the contour for this bending operation.

Machining. The machining of this beam assembly requires some very heavy cutting operations. All surfaces of both the chords and the webs are machined. Equipment used includes both skin and spar mills designed for steel and titanium cutting. Carbide cutters are used and cutter geometries are as reported to the Air Force Machinability Data Center. Surface finishing requirements are 63RHR and are achieved with little hand finishing. Face mill cuts are done with speeds of 100 sfm and feed rates of 15-inches per minute. Depths of cut vary up to 0.250-inch. End mill cuts are done with speeds of 150 sfm and feed rates of 20-inches per minute. Maximum depth of cut is 0.300-inch deep. Figure 9 shows a 6-inch diameter, 14-tooth, face mill with removable insert carbide cutters. These cutters, when worn can be shimmed out and are re-ground up to 12 times before discarding. End mill cuts are made with 4-inch diameter, 12-tooth, helical cutters. Again removable inserts are used. Flat carbide blanks are purchased and are formed by matched ceramic dies using induction heat. Multiple regrinds are possible with these cutters also. Assembly drilling is accomplished in special tools using gantry type drilling equipment to perform the drilling and reaming operations. Figure 10 shows a completed 747 landing gear beam assembly. Each beam contains a total of 22 details--we have described the fabrication of the 5 largest ones.

What's New Within the Industry?

So far our discussion has been devoted to fabrication of detail parts which are joined by mechanical fasteners. Future trends will be toward other joining techniques for primary structural applications.

Welding. Neither resistance nor fusion welding are used for joining primary structures on commercial airlines although titanium is considered a good weldable alloy. Data is being gathered which points to more widespread use of at least fusion weld processes. Highest quality welds are achieved by the electron beam processes, but experience with plasma-arc equipment indicates nearly equivalent quality, with much more operational flexibility.

To increase the flexibility of electron beam welding, two paths are being followed. One is the out-of-chamber concept and the other is to place the weld operation inside a huge vacuum chamber with operators wearing "space suits".

For some applications, mechanized GTA welding provides adequate quality, but an urgent need is for manual equipment in the 75 to 100 ampere range for weld repair or welding of sheet metal gage material. This welding equipment should be manual plasma-arc. Suitable equipment is very nearly ready for the market.

Adhesive Bonding. The use of adhesives for bonding titanium sandwich structure is being considered for both sub and supersonic airplanes. Low temperature service can be satisfied by epoxy resin systems and supersonic service will require polyimide type systems. In both cases, rigorous attention to process control will yield consistently high strength values. Surface preparation of the titanium details is important with both resin systems.

Composite Structure. Designs utilizing the tremendous strengths and modulii of filaments of boron and similar materials will take advantage of the compatible physical properties possessed by titanium alloys. Composite-reinforced titanium structures are particularly effective in stiffness considerations.

Diffusion Bonding. Another promising joining technique is diffusion bonding. Roll bonding is suitable for uni-directional sandwich and integrally stiffened structures, particularly contoured assemblies. Static diffusion bonding has the versatility of making complex assemblies of integrally stiffened structures and for simulated forgings.

A potential production application for diffusion bonding is the 747 landing gear beam assemblies. A design study has been made to redesign this structure to utilize a process called "press bonding" proposed by North American Rockwell Corp. The new design would consist of mirror-image, integrally reinforced webs mechanically fastened together back-to-back. This arrangement requires a minimum of detail parts and joints and yet provides the necessary load path redundency. The press bonding process joins details such as depicted in Figure 11, into an integral assembly shown in Figure 12, in a single processing cycle. Process parameters are such that reliable joining can be achieved using hard vacuum for atmospheric control, bonding pressures of the magnitude of 2000 psi on the joint interfaces, and cycle times of 8 to 16 hours at 1725°F. Advantages of the process are joint reliability, generous joint fillets, repairability, and the ability to make complex assemblies. Disadvantages of the process are the need for special high-tonnage, heated presses and complex expensive tooling. North American Rockwell Corp. has demonstrated the ability to both join smaller sub-assemblies to make a single long section and also to repair defective joints.

Summary

In summary, the industry can look forward to expanded usage of titanium for large aircraft structures. The future use of titanium is limited by two basic restraints. The first is the limitation of capability which is reflected in engineering design as well as manufacturing fabrication ability. The second restraint is cost. END The total cost of fabricating titanium parts can be broken down into non-recurring which includes design, planning, tool design and tool fabrication; and recurring costs which include detail part fabrication, inspection and finishing. It has been shown that fruitful areas of cost reduction lie in both cost areas. Cost reduction efforts must be timed correctly to be successful. Most non-recurring costs are incurred at the outset of the program and usually little opportunity is available to second guess the decisions made during the heat of the initial production pressures. It is important therefore, that careful planning of facilities, equipment, and manufacturing and design capability be done early to ensure that processing decisions will result in lowest program costs.

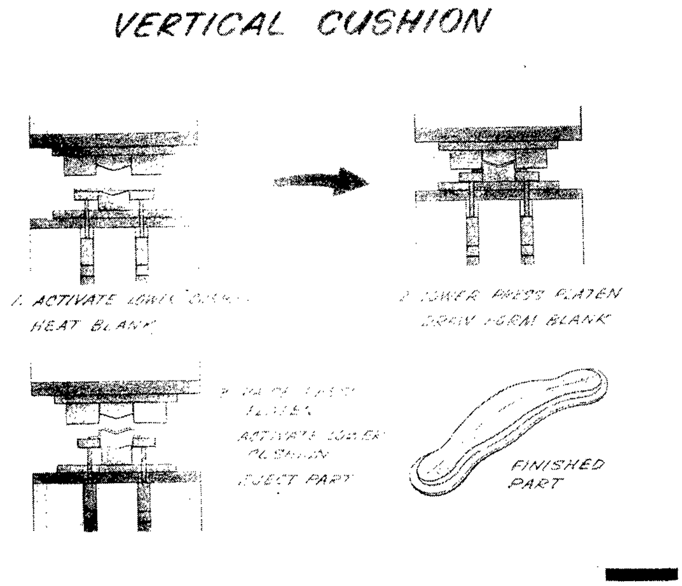

FIGURE 1

HOT DRAW FORMING OPERATION

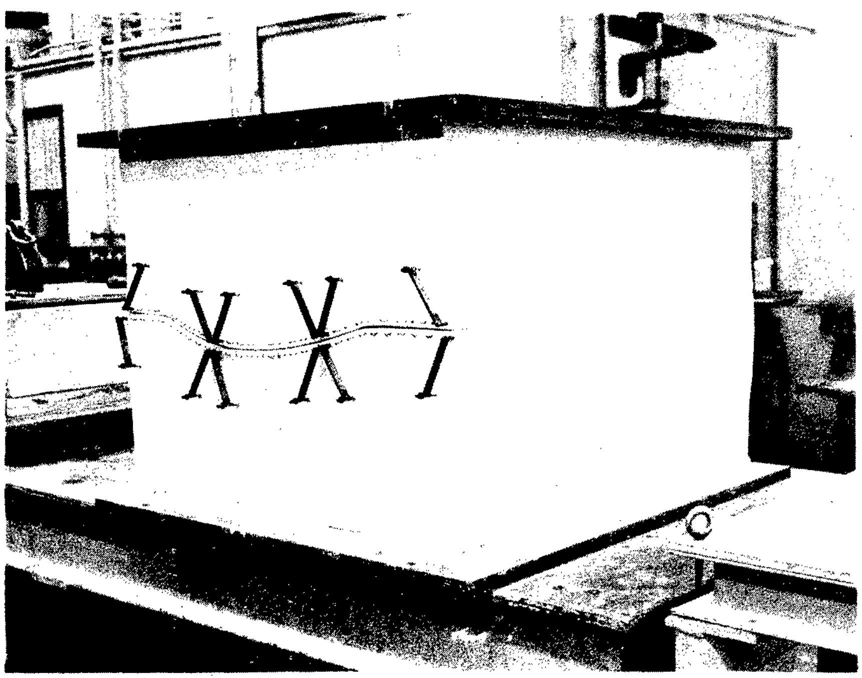

FIGURE 2

INTEGRALLY HEATED CERAMIC DIE SET

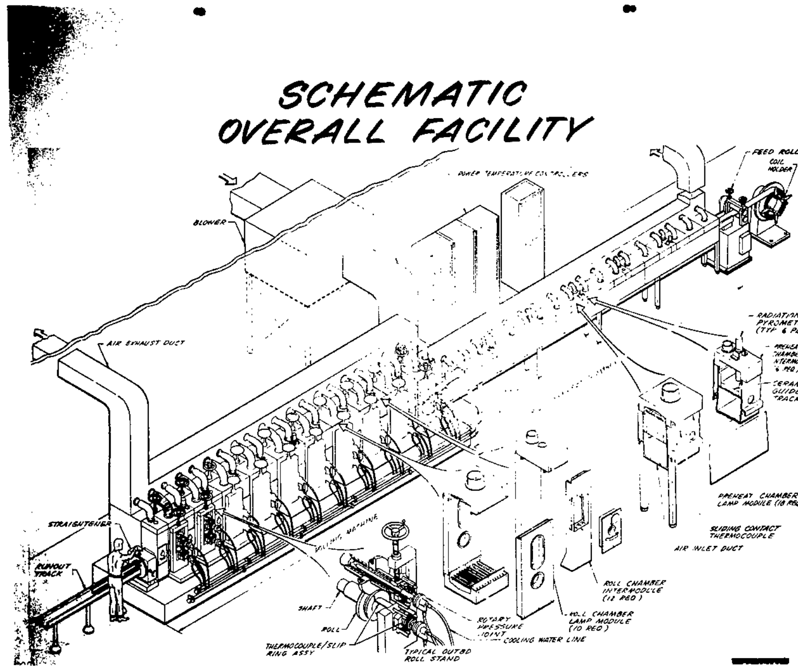

FIGURE 3

SCHEMATIC - AF ROLL FORMING CONTRACT FACILITY

ROLL STAGING FOR HAT SECTION

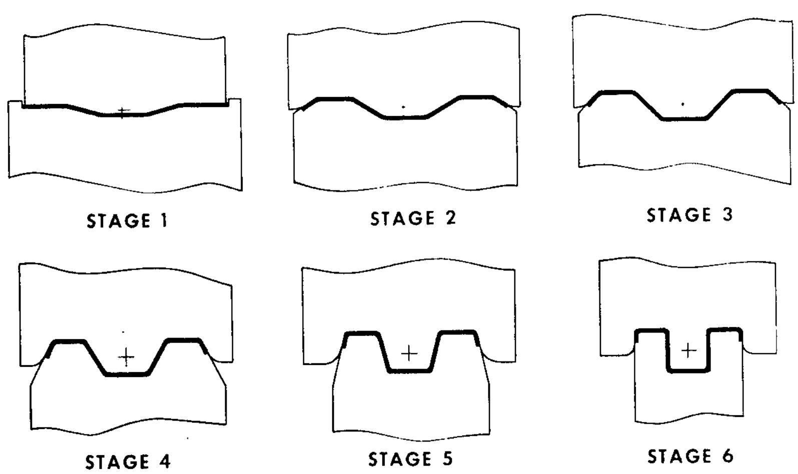

FIGURE 4

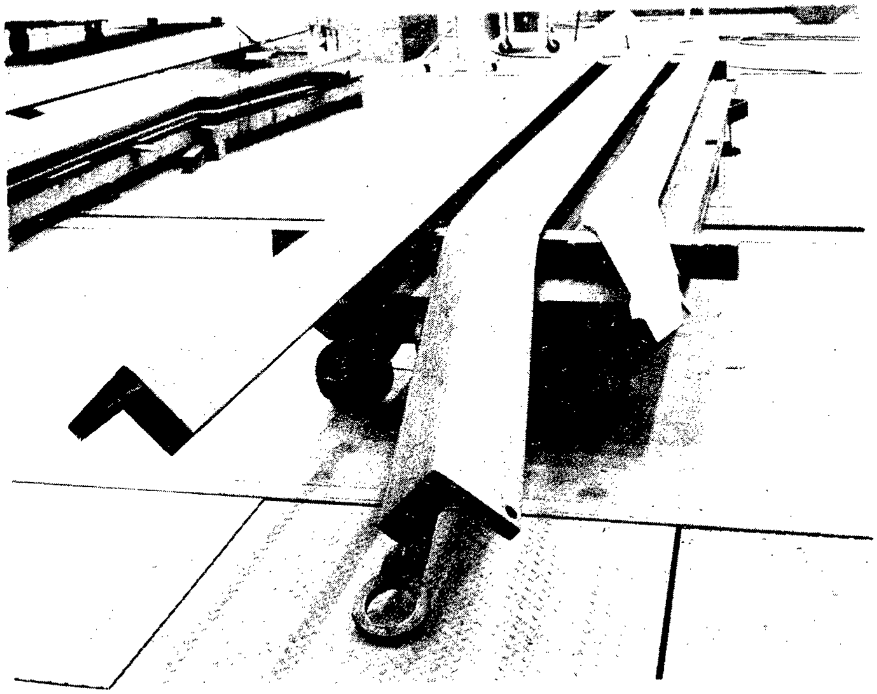

FIGURE 5

747 LANDING GEAR BEAM SPAR
RAW EXTRUSION - FORMED & MACHINED

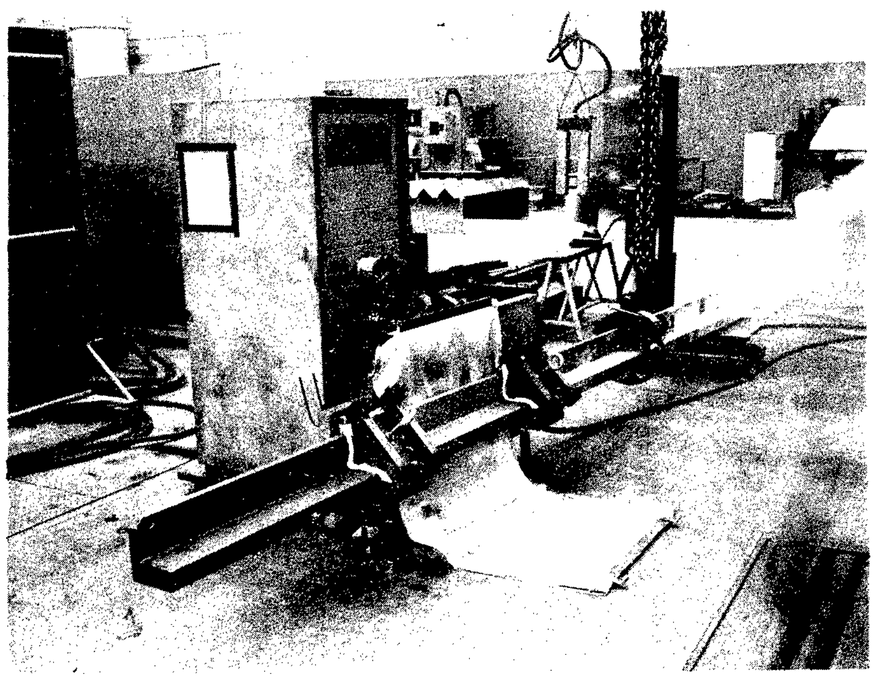

FIGURE 6

PREHEATING EXTRUSION PRIOR TO PRESS FORMING
USING RESISTANCE HEATING

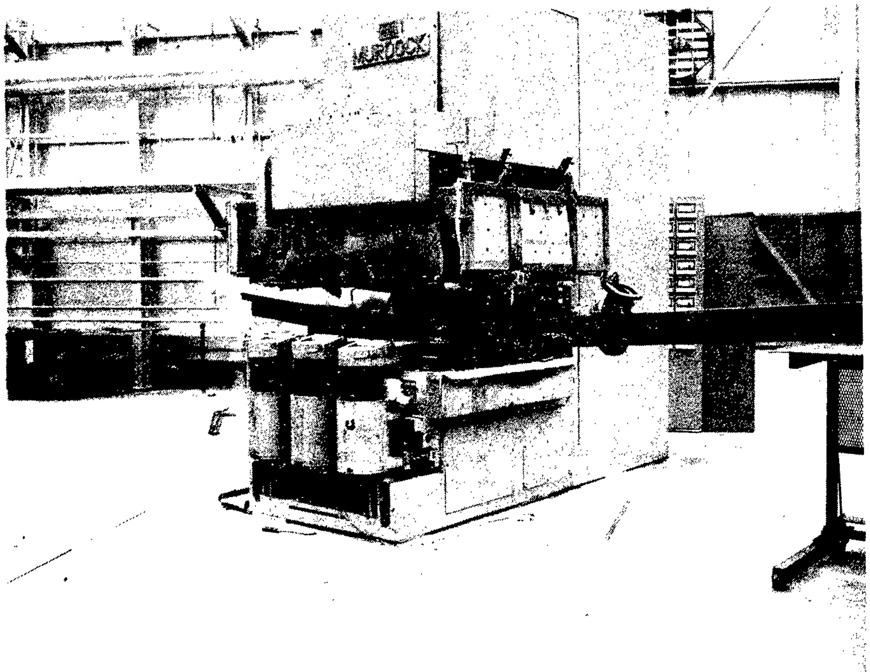

FIGURE 7

PRESS FORMING EXTRUSION

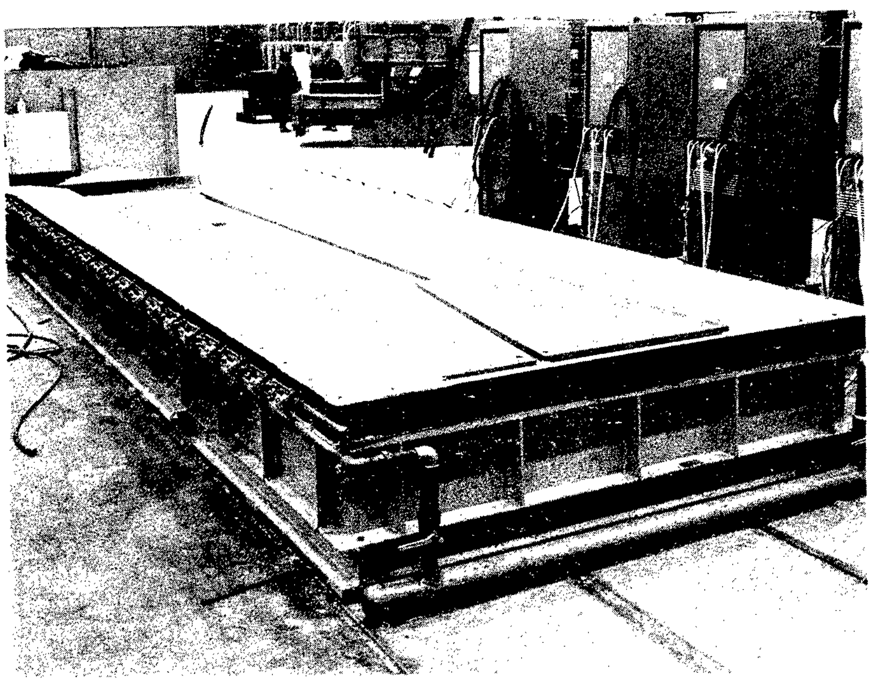

FIGURE 8

CREEP FLATTENING TRIMMED WEB BLANK
USING INTEGRALLY HEATED CERAMIC TOOL

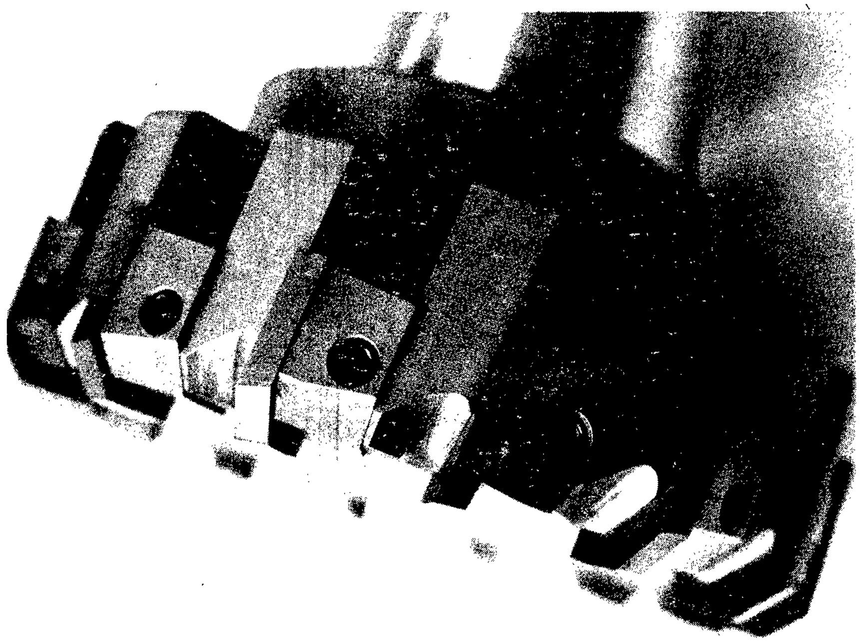

FIGURE 9

16 TOOTH REMOVABLE INSERT FACE MILL

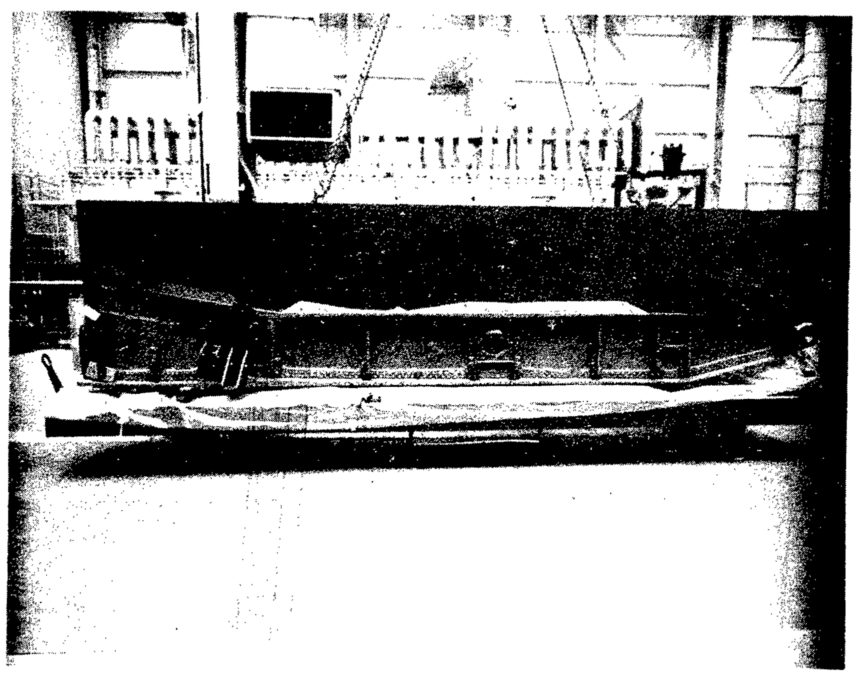

FIGURE 10

COMPLETED 747 LANDING GEAR BEAM ASSEMBLY

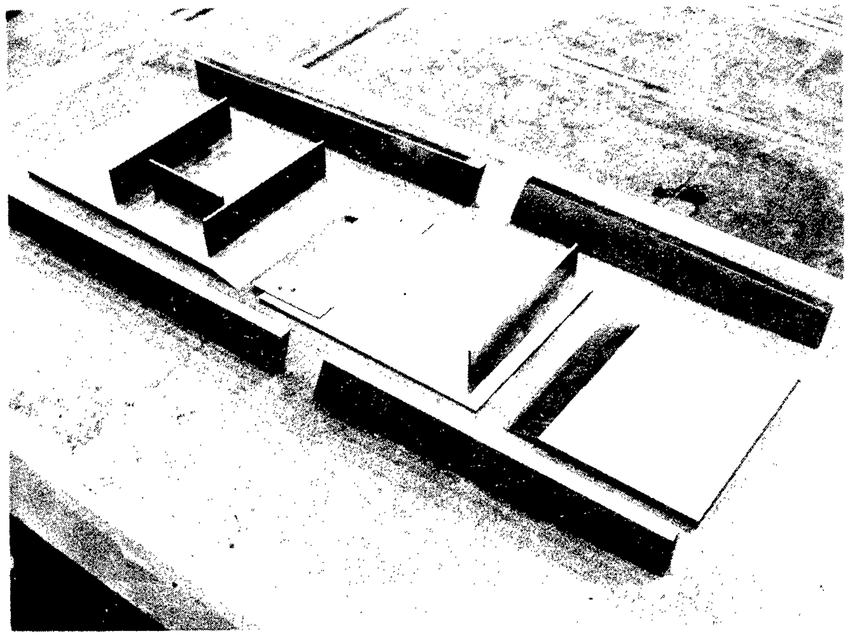

FIGURE 11

DETAIL PART FAMILY - PRESS BONDED ASSEMBLY

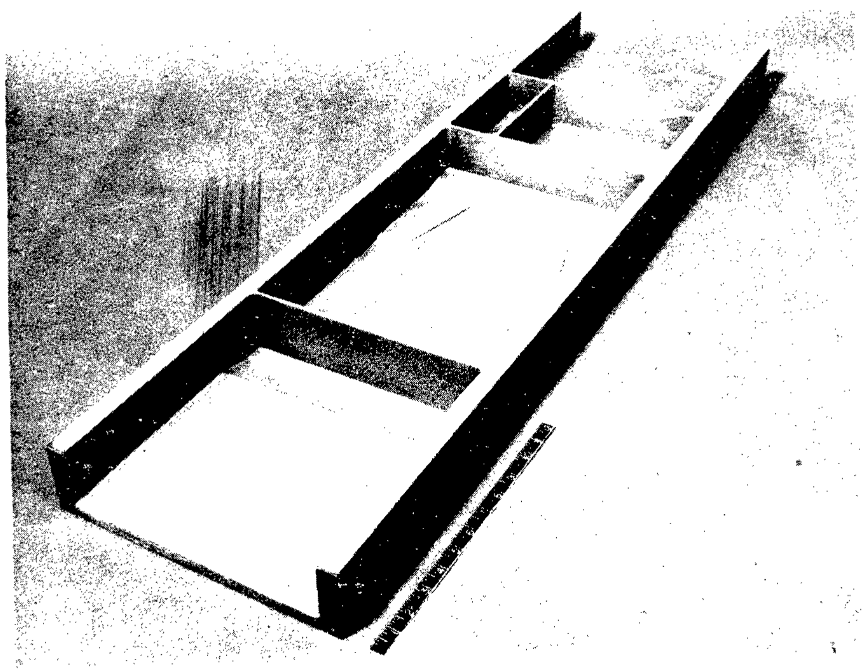

FIGURE 12

TEST ASSEMBLY - PRESS BONDED PROCESS

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